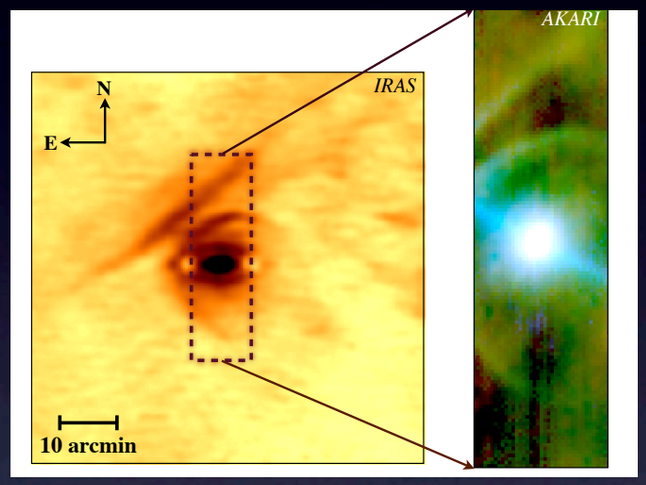
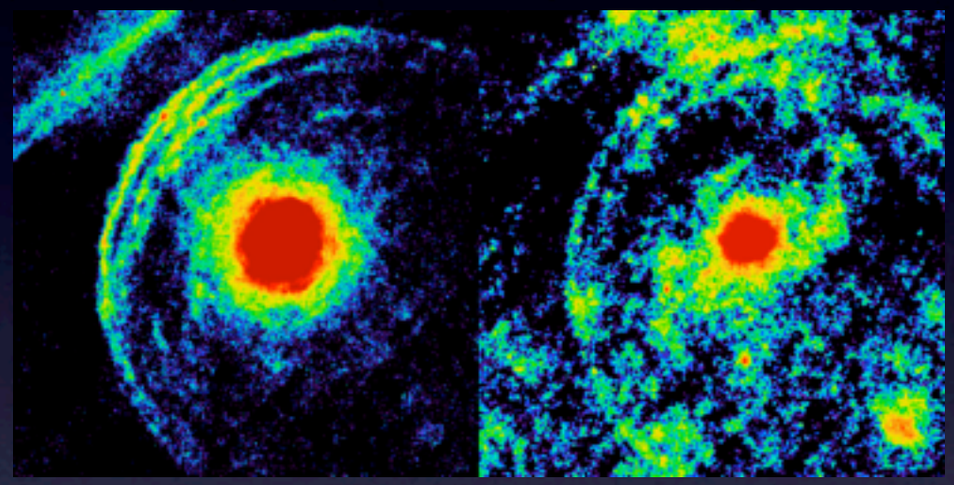
# Double bow shocks around young red supergiants:

## Application to Betelgeuse

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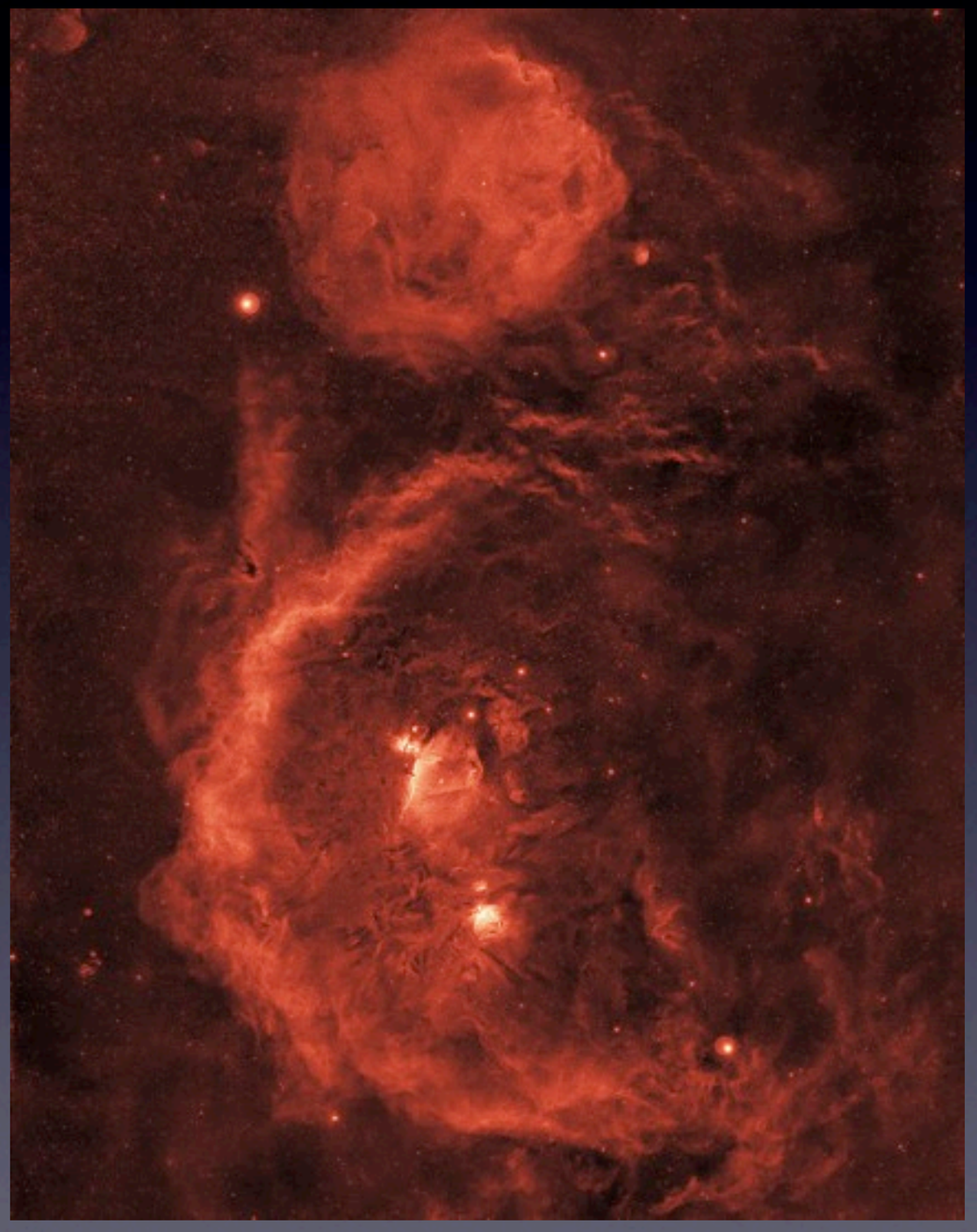
# Outline

- Betelgeuse and its circumstellar medium (CSM).
- Constant wind models (Mohamed, Mackey & Langer, 2012).
- Evolving wind model (Mackey et al, 2012, ApJL, 751, L10).
- 2D simulations of runaway blue supergiant (BSG) star evolving to a red supergiant (RSG) at $V_* = 50$ km/s.
- Comparison of structures to those of the CSM around Betelgeuse.

# Betelgeuse

- H-alpha map of Orion (right).
- D~200pc, (2nd?) nearest RSG to sun.
- Proper motion implies v~28-73 km/s, moving to ~Northeast.
- Mass ~11-20 Msun. Teff ~3300K. (e.g. Neilson+,2011).
- Has mid-IR bow-shock and "bar" upstream from bow shock (Noriega-Crespo+,1997).
- Size similar to the full moon.



# Bow Shock and Bar

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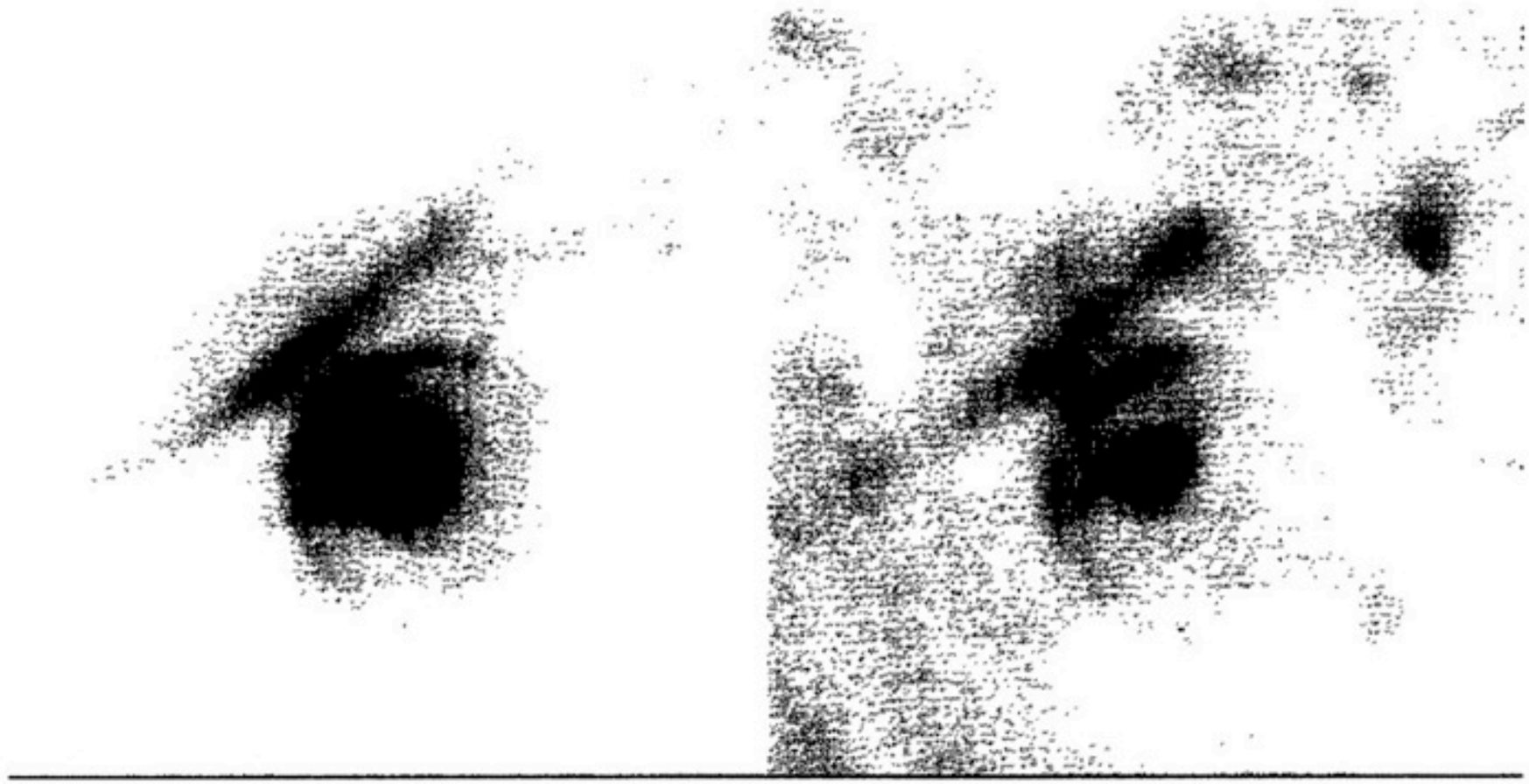
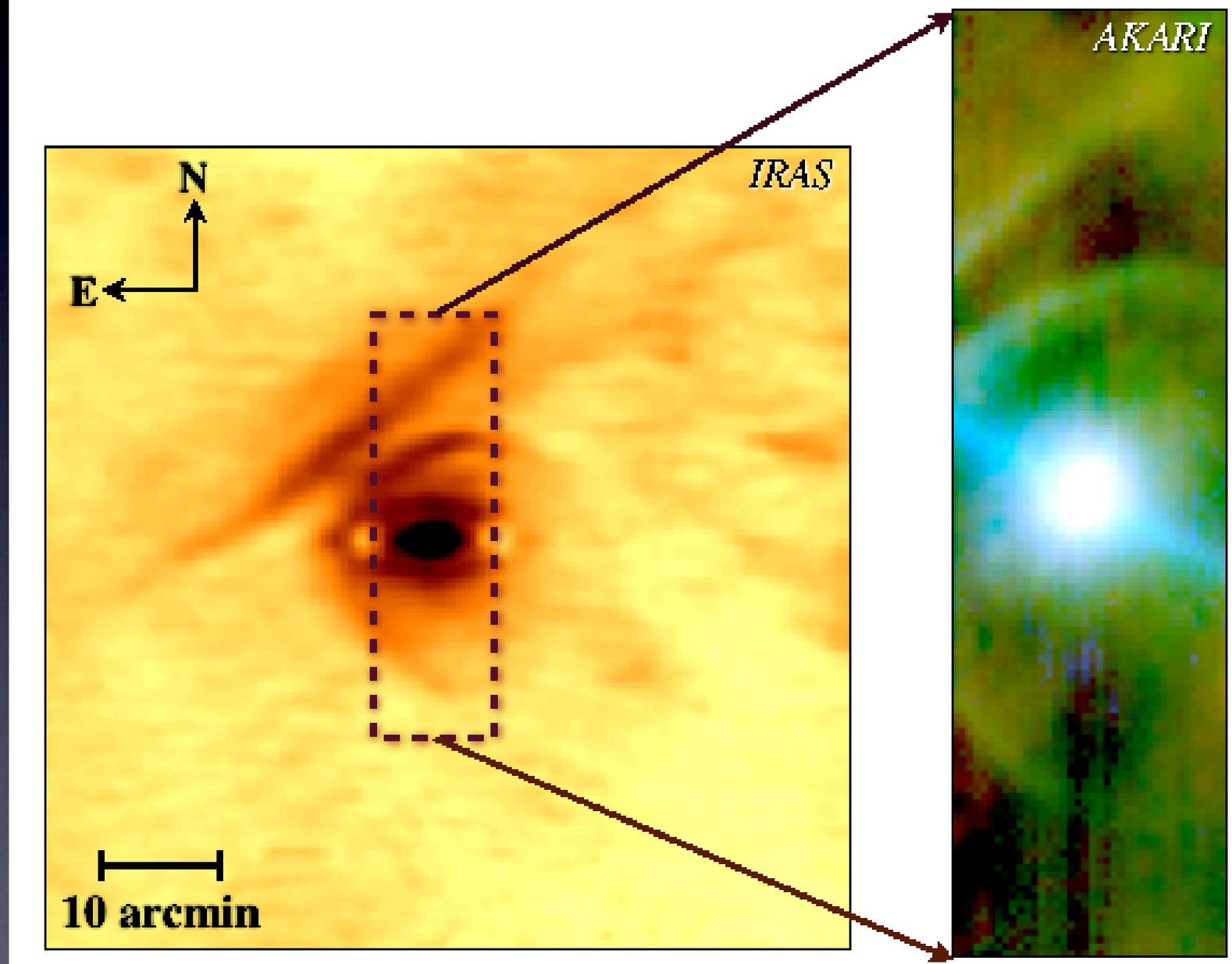


FIG. 1. The 60 $\mu$m (left) and 100 $\mu$m (right) enhance resolution *IRAS* images of $\alpha$ Orionis. The field is approximately one degree.

- IRAS discovery image: 60um (left), 100um (right).
- Mass in bow shock plus wind ~0.033 Msun (for D=200pc).

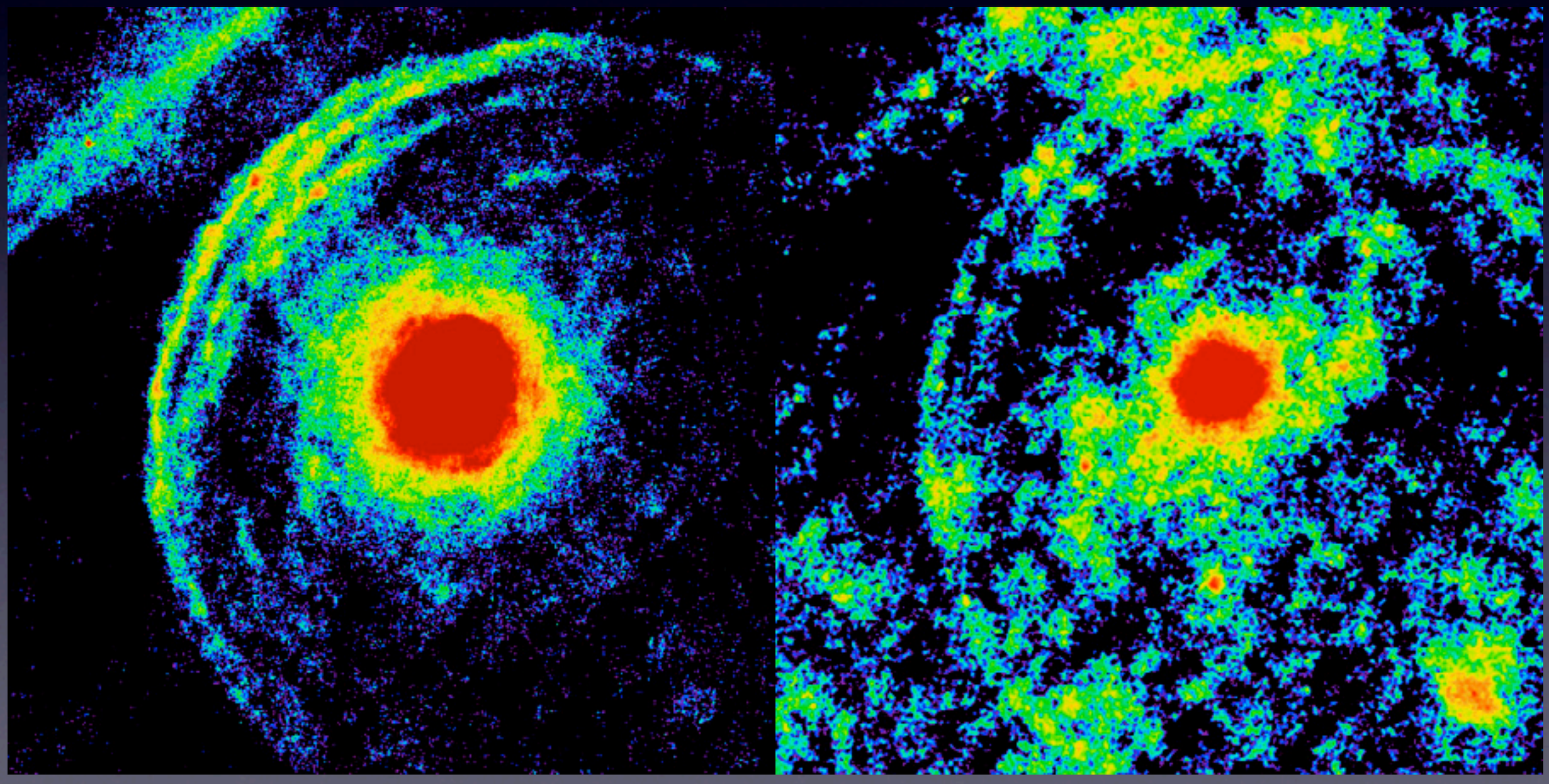
# Bow Shock and Bar

- Reprocessed IRAS image (right).
- Later observed with AKARI (Ueta+,2008,PASJ).
- Higher resolution, smaller FOV.
- Bow-shock has M~0.0033 $M_\odot$, based on AKARI flux.



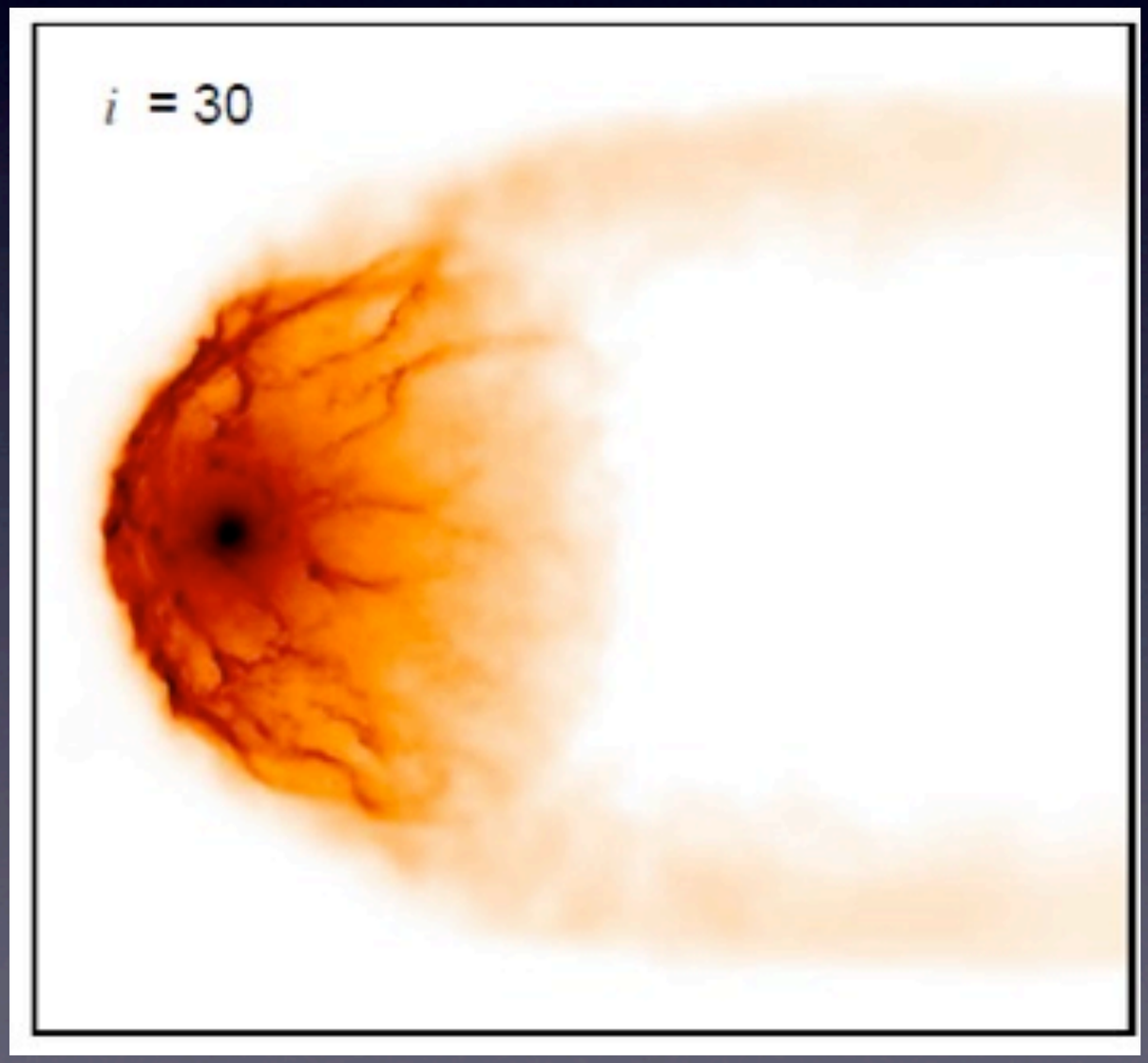
# Bow Shock and Bar

- Herschel 70 + 100 micron (Cox+, 2012,A&A,537,A35). Bow shock mass estimated at ~0.002 $M_o$ (up to 0.28 $M_o$).



# Mohamed, Mackey & Langer (2012) (see previous talk)

- 3D SPH simulations of constant RSG wind interacting with ISM flowing past star, generating bow shock.
- Different ISM densities, stellar space velocities.
- Bow shock is clumpy and unstable, and mass is >0.1$M_\odot$ in steady state.
- If M=0.0033$M_\odot$, bow shock must be <30 kyr old.
- So maybe the wind is evolving?



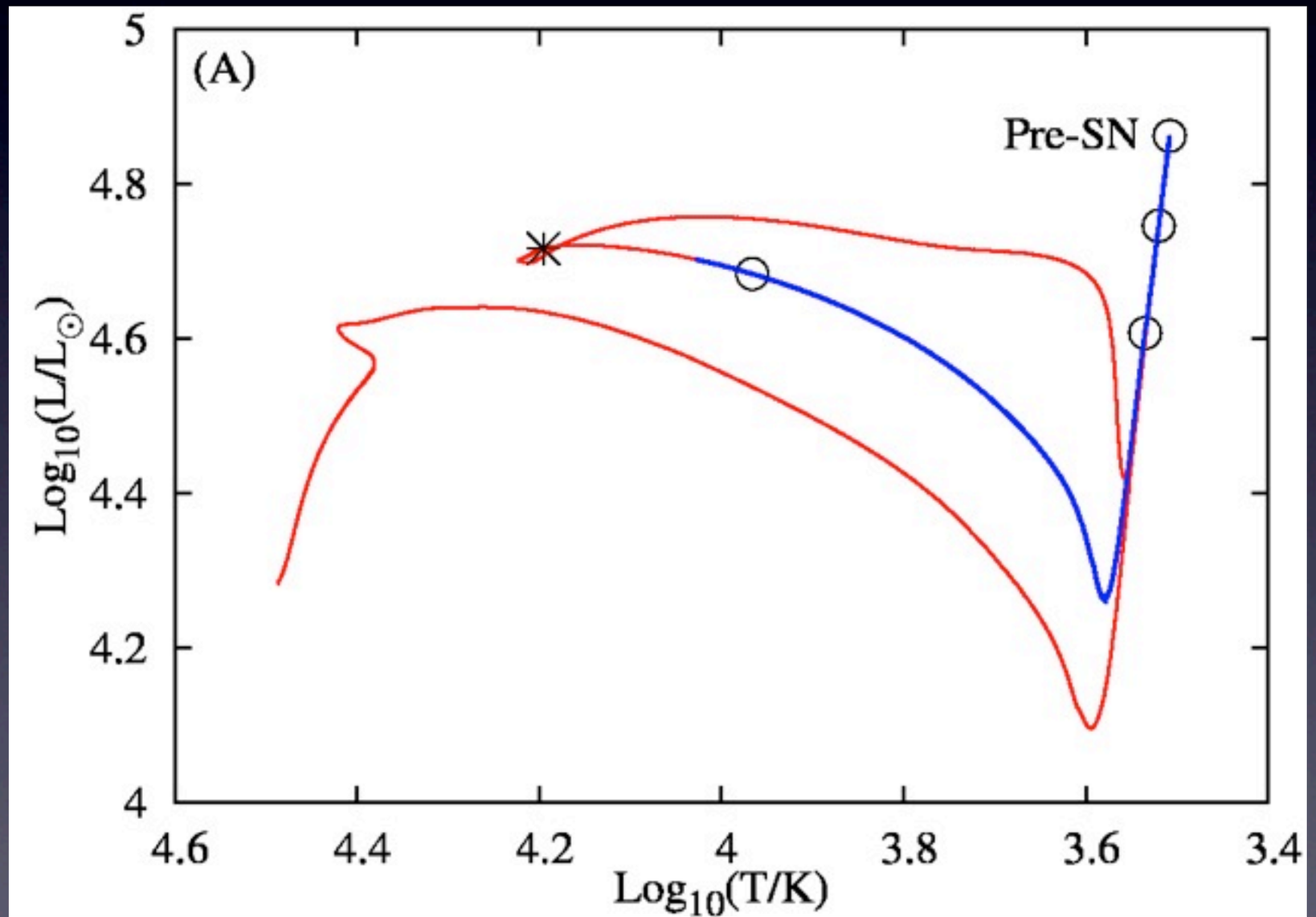
# Why care?

- If the bow shock is really young, then either Betelgeuse or the ISM has changed.
- No clear evidence that the ISM has changed.
- CSM shows relics of previous mass loss, rather like tree rings showing climate history.
- We can learn about Betelgeuse's past, and therefore also its future.
- We know so little about its fundamental parameters, so any constraints are valuable.

# Evolving wind model

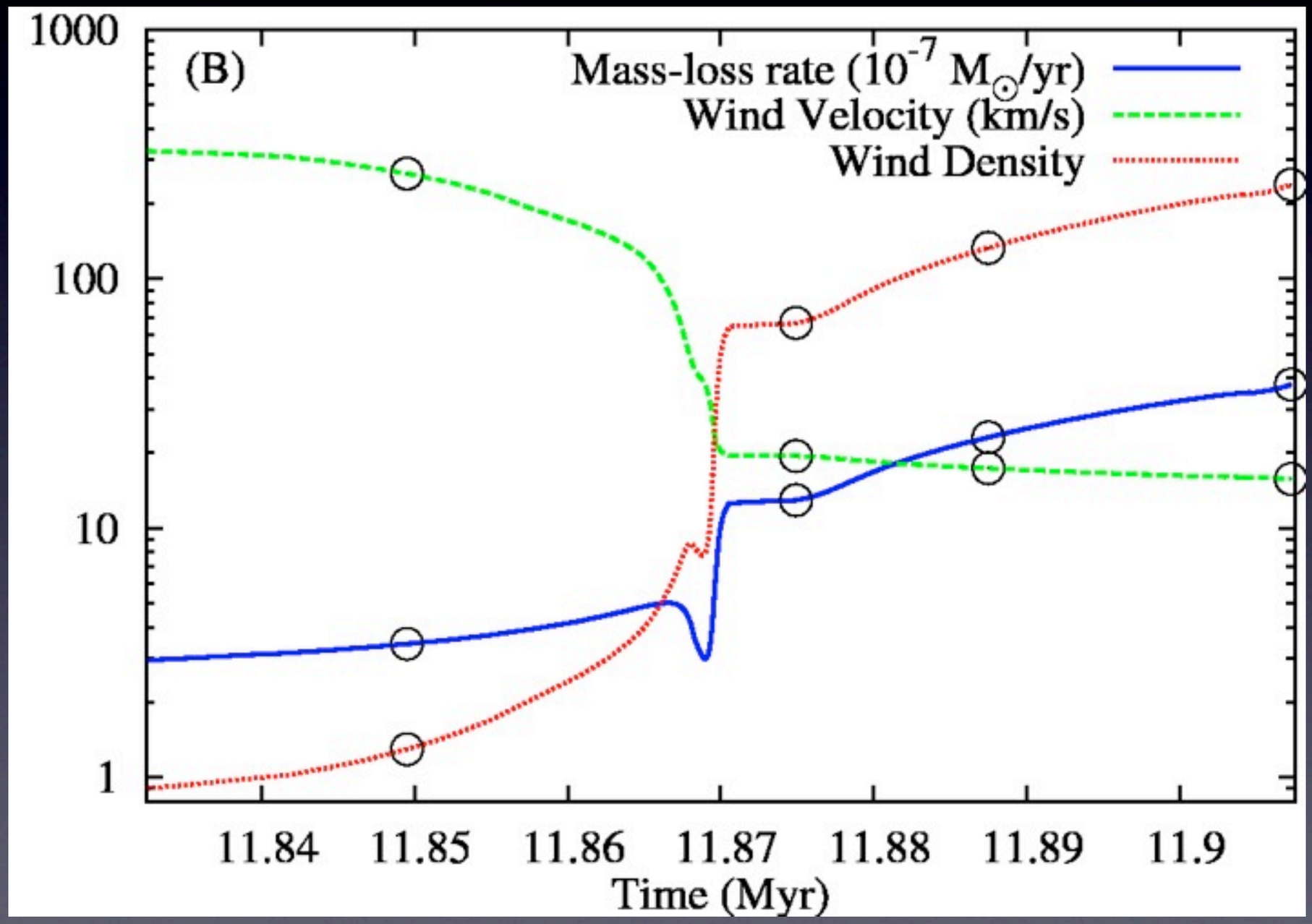
- Use Bonn stellar evolution code (Yoon & Langer, 2005), with mass loss from Kudritzki+(1989), de Jager+(1988), and wind velocities from Eldridge+(2006) with slower RSG wind.

- 15 $M_o$ model.
- Computed to have RSG properties similar to Betelgeuse (see Neilson+2011).
- Simulation starts at 11.4 Myr, shown by asterisk.
- Blue section lasts 75 kyr (from 11.832 to 11.907 Myr).



# Stellar Wind Properties

- Last 75 kyr of evolution (blue region of previous plot).
- Mdot, $V_w$, and wind density plotted.
- Kink is due to luminosity dip.



# 2D Hydrodynamical Simulations

- 2D simulations of (z,R) plane with cylindrical symmetry.
- Collisional ionisation equilibrium gas cooling (Wiersma+2009).
- Star has V*=50 km/s, through ISM with n(H)=0.2cm-3
- Star is static on grid, ISM flows past (right to left).
- Freely-expanding wind imposed in region r<0.05 pc (Freyer+, 2003).

# Movie of density/temperature

http://www.astro.uni-bonn.de/~jmackey/Betelgeuse2012/BSG2RSG_full.mpeg

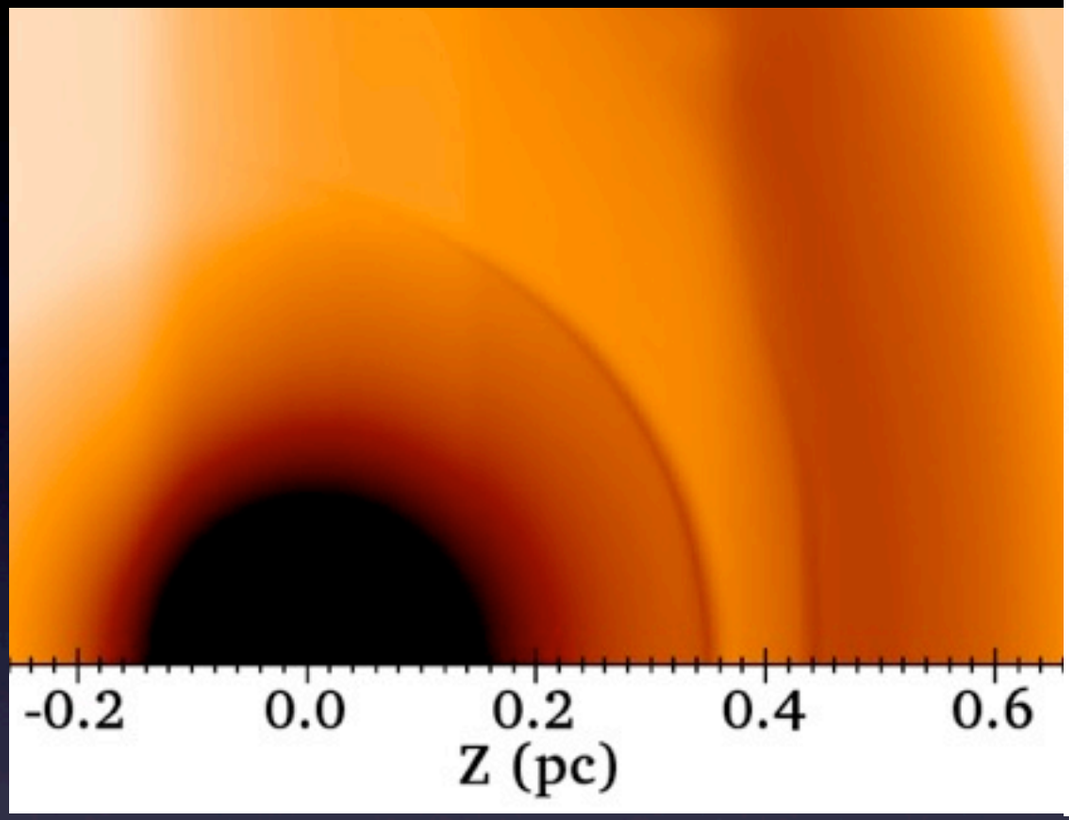
http://www.astro.uni-bonn.de/~jmackey/Betelgeuse2012/BSG2RSG_end.mpeg

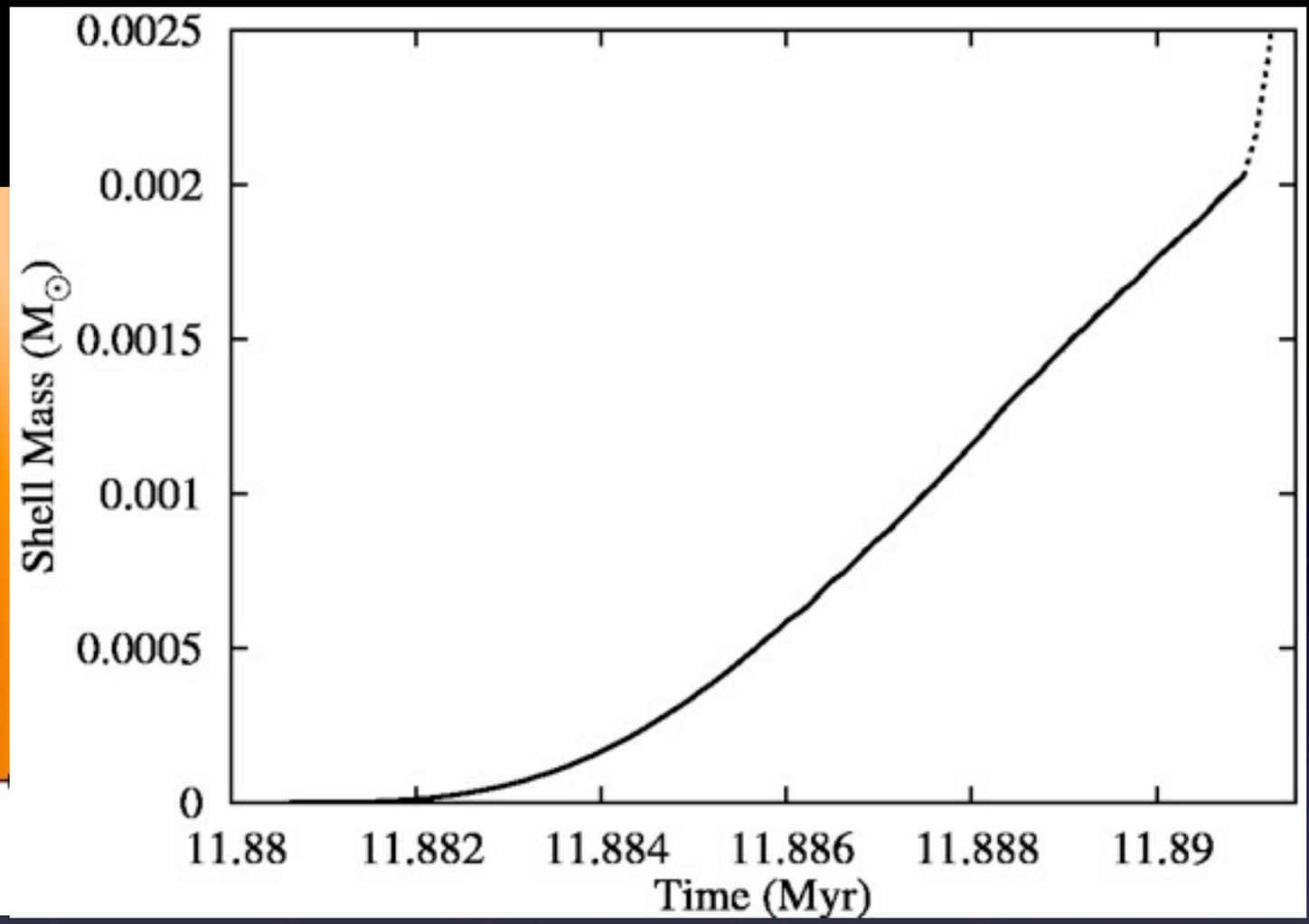
Projected Gas Density (g/cm2)

movie of projected density

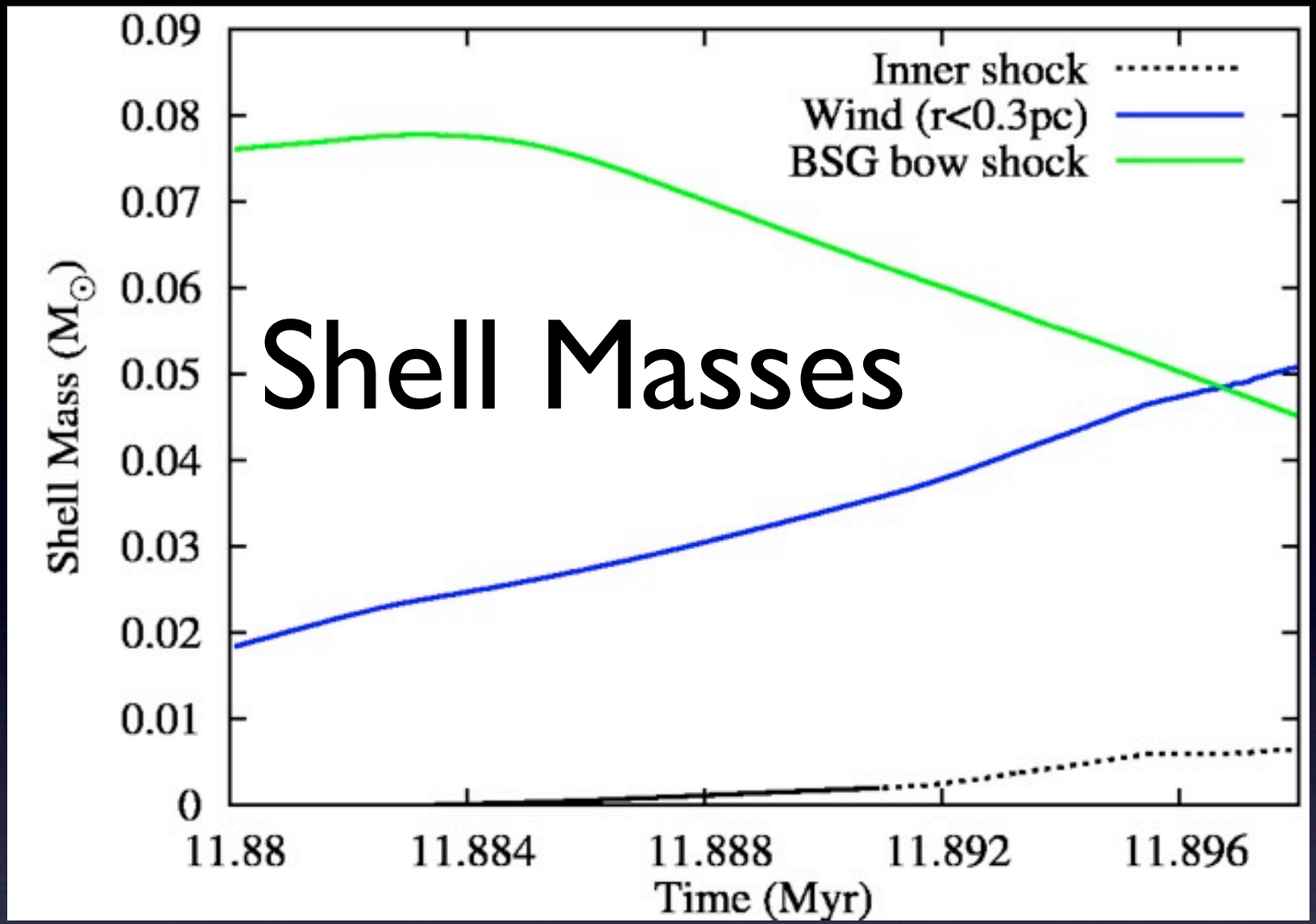
http://www.astro.uni-bonn.de/~jmackey/Betelgeuse2012/AOri_M15_n0p2_v50_dr0025_proj.mp4

# Shell Mass



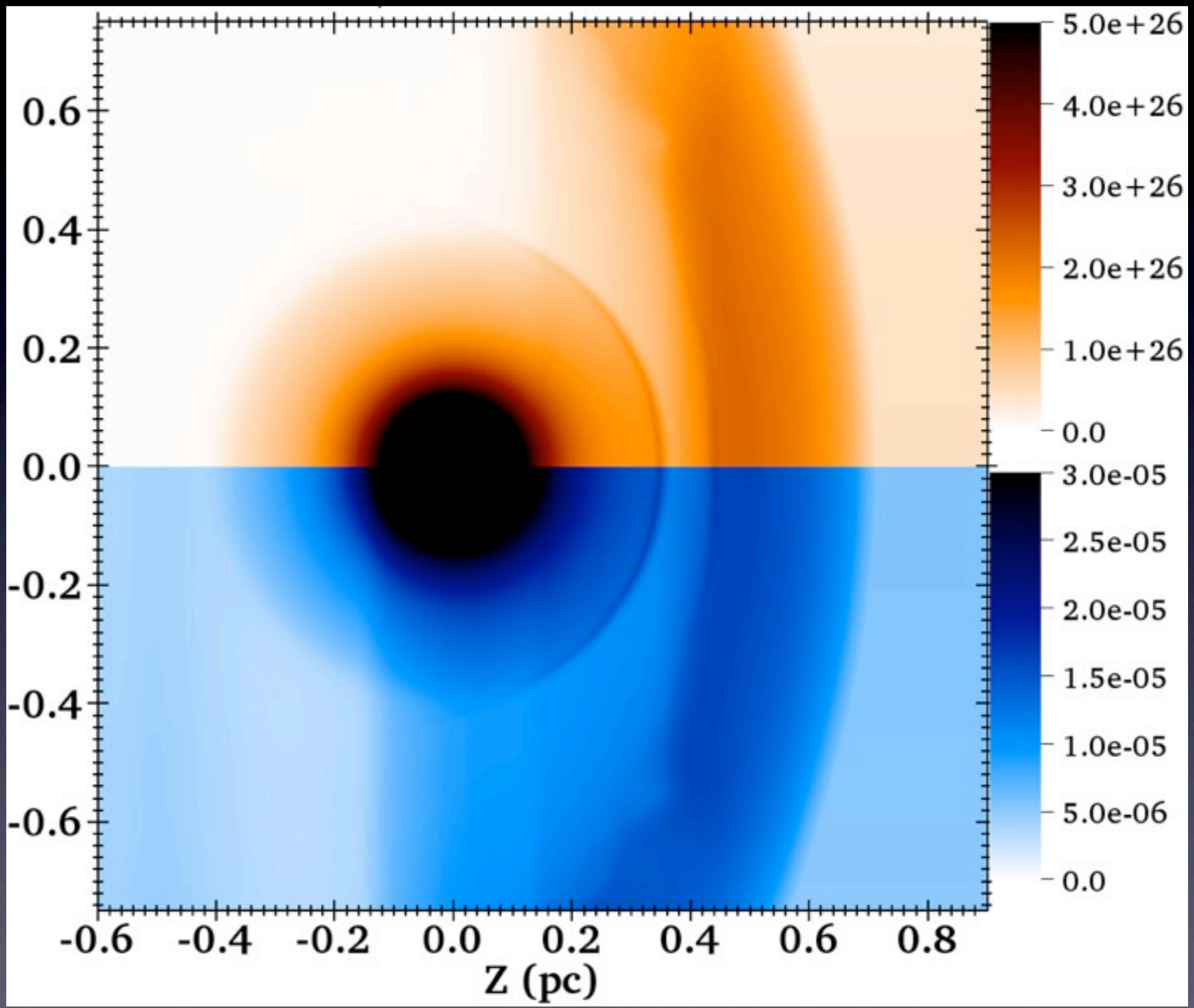

- Mass of inner shell measured from simulations during time between BSG reverse-shock collapse and contact discontinuity collapse.
- Mass ~50% lower than AKARI mass estimate, but within a factor of 2.
- Similar to Decin+(2012) mass, but not Cox+(2012).




- Inner shell much less massive than remnant of outer BSG bow shock, and inner RSG wind.
  - Le Bertre+(2012): $M_{wind}$~0.086$M_o$.
  - Decin+(2012): $M_{wind}$~0.02-0.07 $M_o$ (21cm), $M_{bar}$~0.002-0.029$M_o$, $M_{arc}$~0.0024 $M_o$.
  - Cox+(2012): $M_{arc}$~0.16-0.28$M_o$ (different dust + distance).

# Dust Emission

- Projected dust luminosity (above), and mass surface-density below.
- Fairly standard assumptions about dust absorption/ emission/ abundance.
- Dust is simply re-radiating stellar flux.



# Conclusions

- 15-20 $M_\odot$ runaway stars evolving from MS/BSG to RSG can produce multiple bow shocks/shells during transition.
- They are a generic feature of blue-to-red transitions.
- May be visible for 50-100 kyr (depending on parameters).
- Our model can match Betelgeuse's bow shock in terms of location (~0.3pc upstream) and maybe mass (2e-3$M_\odot$).
- Provides a natural explanation of the upstream bar.
- If Betelgeuse was recently a BSG, with our model it would be ~15 kyr from supernova.
- Caveats: masses of shocks, curvature of bar, $V_*$ in model.
- See Mackey, Mohamed, Neilson et al., (2012, ApJL, 751, L10).